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Changes to flood peaks of a mountain river: implications for analysis of the 2013 flood in the Upper Bow River, Canada

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Abstract:

The mountain headwater Bow River at Banff, Alberta, Canada, was subject to a large flood in June 2013, over which considerable debate has ensued regarding its probability of occurrence. It is therefore instructive to consider what information long-term streamflow discharge records provide about environmental change in the Upper Bow River basin above Banff. Though protected as part of Banff National Park, since 1885, the basin has experienced considerable climate and land cover changes, each of which has the potential to impact observations, and hence the interpretations of flood probability. The Bow River at Banff hydrometric station is one of Canada's longest-operating reference hydrological basin network stations and so has great value for assessing changes in flow regime over time. Furthermore, the station measures a river that provides an extremely important water supply for Calgary and irrigation district downstream and so is of great interest for assessing regional water security. These records were examined for changes in several flood attributes and to determine whether flow changes may have been related to landscape change within the basin as caused by forest fires, conversion from grasslands to forest with fire suppression, and regional climate variations and/or trends. Floods in the Upper Bow River are generated by both snowmelt and rain-on-snow (ROS) events, the latter type which include flood events generated by spatially and temporally large storms such as occurred in 2013. The two types of floods also have different frequency characteristics. Snowmelt and ROS flood attributes were not correlated significantly with any climate index or with burned area except that snowmelt event duration correlated negatively to the Pacific Decadal Oscillation. While there is a significant negative trend in all floods over the past 100 years, when separated based on generating process, neither snowmelt floods nor large ROS floods associated with mesoscale storms show any trends over time. Despite extensive changes to the landscape of the basin and in within the climate system, the flood regime remains unchanged, something identified at smaller scales in the region but never at larger scales. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS floods; snowmelt; rain-on-snow; Canadian Rockies; return periods; hydroclimate trends

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INTRODUCTION

Whether or not flood magnitudes are changing with climate is a question of considerable hydrological interest and a concern to insurers, decision-makers, scientists, engineers, and the general public. The 2013 flood in the Bow River Valley of Alberta, Canada, alone resulted in a profusion of opinions regarding this 'flood of the century' in the media, governments, and professional workshops. The daily streamflow series for the Bow River at Banff is a dataset that can be used to address the question of change over time as the hydrometric station has a record in excess of 100 years, is of high quality, and drains a basin that whilst not unchanged over the past is a protected area in Banff National Park with well-documented land management and no substantive water management.

Floods in the Bow River have attracted attention over time (Dawson, 1886; Sauder, 1914; Whyte, 1914, 1916; Ford, 1924; Hoover 1929; Hoover and MacFarlane, 1932). Bow River floods have been attributed to the effects of forest fires by Dawson (1886) and in the histories of Banff National Park (Hart, 1999, 2003). Armstrong *et al.* (2009) reported large floods in the Bow River in 1879, 1897, 1902, 1915, 1929, and 1932 and lesser floods in 1916, 1923, 1933, 1948, and 1953 and suggest that floods had diminished over time, but noted that these large floods were associated with heavy widely distributed rains; however, their remarks were made before the rain-on-snow (ROS) flood events in 2012 and 2013.

The Bow River at Banff hydrometric station has been operated for more than 100 years, and it is one of the longest records of stations in Canada's Reference

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Hydrologic Basin Network. Reference stations in the Reference Hydrologic Basin Network were selected to provide records that were suitable for studies of the relationship between streamflow and climate (Brimley *et al.*, 1999; Whitfield *et al.*, 2012). Burn *et al.* (2012) demonstrate the importance of reference networks for detection of climate-driven trends. Other studies have made frequent use of the data from this station (e.g. Hopkinson and Young, 1998; Rood *et al.*, 2008; Burn and Whitfield, 2016; Rood *et al.*, 2016). Burn and Whitfield (2016) examined trends in reference and non-reference hydrometric stations in Canada and found different patterns between the two types of stations and in different regions. Using the Mann–Kendall test and the annual maximum series, rivers such as the Bow were showing significant declines in flood magnitude and the peaks were occurring earlier. Burn and Whitfield (2016) demonstrated that this also applied to flows of Q10 and Q0.5; these are the 90th and the 99.5th quantiles, respectively.

In most years, the Bow River is a classic nival system; the annual peak flows generally result from spring/summer snowmelt (Pomeroy *et al.* 2016a). Hoover (1929), however, identified three conditions required for the very largest floods in the Bow River: a large snowpack, a late spring, and hot weather with torrential rain; conditions that occurred during the 2013 major ROS event in the Bow River Basin (Milrad *et al.*, 2015; Pomeroy *et al.*, 2016a,b; Liu *et al.*, 2016; Fang and Pomeroy, 2016) and the smaller 2012 event. This complicates the problem of assessing the properties of floods, particularly return periods and trends; normally, the peak flows in the Bow River at Banff are from snowmelt, but on rare occasions, large events occur that are the result of widespread ROS and result in some of the largest observed and reported peaks. A persistent issue in the study of floods is how to address the mixture of flood-generating mechanisms that occur in many flood event series (Whitfield, 2012). The classic literature (Moran, 1957; Waylen and Woo, 1982, 1983; Woo and Waylen, 1984) demonstrates the impacts on the frequency analysis of mixed flood series for annual maxima. An alternative approach involves the analysis peaks over threshold (e.g. Hirschboeck, 1987); neither method has fully resolved dealing with mixed populations. Separation of event types is not a routine calculation nor has it been successfully automated; however, standard approaches to frequency analysis or trend analysis of a flood series from mixed processes may not adequately or fairly reflect reality.

While the intention of reference basin sites is that land use does not change over time, it is clear that since 1885, numerous events and actions have resulted in many changes to the Bow River Basin in Banff National Park. These include the linear developments of the railway in the 1880s and the development of highways (Hart, 1999), exclusion of First Nations from the park (Binnema and Niemi, 2006), the suppression of forest fires (White, 1985), and a changing climate. Each of these has contributed to landscape changes that have been observed over the past century, most notably the reduction of glacier area by 25% (Luckman, 1998; Hopkinson and Young, 1998; Comeau *et al.*, 2009) and the expansion of coniferous forest and reduction in grassland area (Byrne, 1964; Nelson and Byrne, 1966; Luckman, 1998).

Banff National Park, with an area of 6600 km^2, was established in 1885 in the Canadian Rocky Mountains. The park follows the main valley of the Bow River through mountainous terrain with glaciers and icefields. Three ecosystems are represented in the park: montane (~3%), subalpine (~53%), and alpine (~27%). Forests cover 44% of Banff National Park, primarily in valley bottoms and lower mountain hillslopes (Van Wagner *et al.*, 2006). The tree line is approximately 2300 m. Holland (1982) reports that in Banff and Jasper, wetlands with poorly drained soils occupy only 8% of the area, with 53.5% being well-drained or upland soils and 38.6% being miscellaneous types.

The role of forest fires in relation to floods in the Bow River was first suggested by Dawson (1886) but subsequently by others. Fire occurrence records for Banff National Park provide a basis to assess the importance of fire to flood regime. Fire is an important component of the mountain ecosystem (Feunekes and Van Wagner, 1995; White *et al.*, 1998, 2007, 2011) and is also strongly connected to the climate system (Johnson and Fryer, 1987; Johnson and Wowchuk, 1993). Fire suppression in Banff National Park began in the 1920s (White, 1985) and continued until the 1980s when a programme of prescribed burns began (White, 1985). Fire is recognized as being important to the grassland ecosystem (Ogilvie, 1963; Day, 1972; Stringer, 1973) and also to the elk introduced to the park (White *et al.*, 1998; White, 2001). River basins directly impacted by fire exhibit a variety of hydrological responses (Moody and Martin, 2001; Chanasyk *et al.*, 2003; Mahat *et al.*, 2015; Springer *et al.*, 2015), including hydrophobicity and decreased infiltration (Robichaud 2000). Evergreen forests intercept and sublimate a large fraction of winter snowfall (Pomeroy *et al.*, 1998) and slow snowmelt substantially (Ellis *et al.*, 2011). Pomeroy *et al.* (2012) have shown through modelling a substantial increase in spring runoff with forest cover removal in Marmot Creek basin, near to the Upper Bow River Basin, and Fang and Pomeroy (2016) show that if soils are disturbed along with the canopy, then the 2013 modelled flood peak discharge doubles compared with current primarily forested conditions in Marmot Creek. The modifications to the fire regime from fire suppression coupled with the careful record keeping by the National Park Wardens permit the

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assessment of the relationship of fire and floods in the relatively larger Bow River Basin.

There is considerable literature indicating that climate and streamflow respond to variations in large-scale features of the climate system (Fleming *et al.*, 2007; Fleming and Whitfield, 2010). Two climate system features that are reported to be important in western Canada are the El Niño–Southern Oscillation (Trenberth, 1997; Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Budikova and Nkemdirim, 2005; Fleming and Whitfield, 2010; Harder *et al.*, 2015) and the Pacific Decadal Oscillation (PDO; Mantua and Hare, 2002; Burn, 2008; Déry and Wood, 2005; Fleming and Whitfield, 2010; Whitfield *et al.*, 2010; Fleming and Sauchyn, 2013; Harder *et al.*, 2015). Two other oscillations that affect North America are the North Atlantic Oscillation (NAO; Hurrell *et al.*, 2001; Burn, 2008) and the Atlantic Multidecadal Oscillation (AMO; Enfield *et al.*, 2001; Fortier *et al.*, 2011; Veres and Hu, 2013).

The basin of the Bow River at Banff, though protected, is subject to climate changes and land cover change from fire and its suppression. The objective of this paper is therefore to address two main questions. First, are there any trends in flood attributes in the record from the Bow River at Banff and of high flows in general?, and second, are there relationships between the flood attributes and changes in land cover or changes in the climate system over the basin? A peaks over threshold approach is used to consider all flow events that exceed the 90th quantile ($104\,m^3/s$); for each event, three quantities were extracted: (1) the maximum value, (2) the event volume, and (3) the duration of the event. The annual series of these attributes, including the number of events in each year, were examined for trends and frequency analysis for separated series based upon generating process.

SITE AND METHODS

Summers in the Upper Bow River Basin are brief and cool with an occasional hot day, whilst winter is normally long with an occasional cold spell (Janz and Storr, 1977; Harder *et al.*, 2015). The weather is notable for its variation from season-to-season, day-to-day, and even hour-to-hour. There is a strong precipitation gradient from west to east; semi-arid valleys have less than 500 mm of precipitation (Janz and Storr, 1977). Topography and elevation play a predominant role in all elements of climate; differences in elevation drive local variations in climate. During the winter, from September to April, precipitation at Lake Louise follows a similar monthly pattern to Vancouver; during May to August, this switches to a pattern similar to Calgary (Janz and Storr, 1977); this suggests that summer precipitation is convective (Calgary regime) and winter is frontal (Vancouver regime). Precipitation at Lake Louise (~750 mm) is about 50% greater than that at Banff (~500 mm). The maximum precipitation in Banff occurs in June, whilst at Lake Louise, it is in December. The total annual snowfall is directly related to elevation; valley observing stations receive much less snowfall than that occur at higher elevations (Janz and Storr, 1977).

Many studies of floods use the annual maximum series; here, all events that have observations of discharge that exceed the 90th quantile were examined, the intention being to sample more than one event in each year. The daily discharge for the Bow River at Banff (05BB001) was obtained for the period of record by using ECDataExplorer (up to 2012); additional data for 2013–2015 were obtained from the Water Survey office in Calgary (D. Lazowski, personal communication). Daily temperature and precipitation for the series of climate stations operated at Banff (3050520) were extracted from the Environment Canada climate archive and merged by using the R package 'seas'. The locations of these two stations are shown in Figure 1, which also shows the boundary of Banff National Park, the distribution of forested area, and the location of the stream gauge at

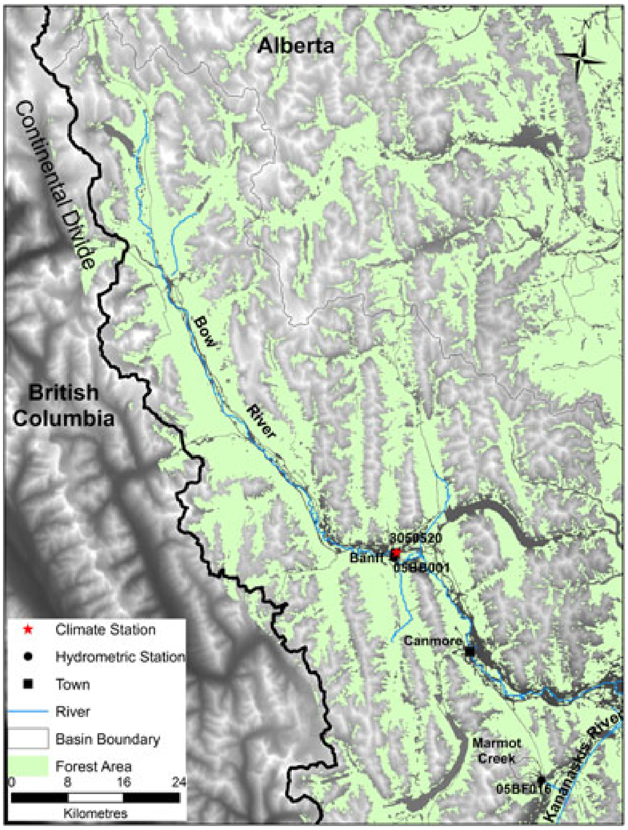

Figure 1. Bow River Valley in Banff National Park showing the locations of climate and hydrometric stations and forested areas. The location of the Marmot Creek Research Basin is also shown

Marmot Creek. Annual and climate indices, AMO, NAO, Southern Oscillation Index (SOI), and PDO, were obtained from the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/psd/data/climateindices/list/).

Flood event data were extracted from the daily flow series. Each time the daily flow series exceeded the Q90 threshold, attributes were obtained: starting date, event maximum (the maximum discharge during the event), volume (the total discharge during the period discharge was above the threshold), and duration (the total number of days above the threshold). Q90 was chosen as it approximates the smallest of the annual maxima series. The Q90 snowmelt series may contain a few smaller runoff events in August or September, where glacial melt in warm spells or other processes may be occurring (Hopkinson and Young, 1998). Nine events for which there were streamflow data were identified as large ROS events as described in the succeeding texts. The event data were subsequently converted into two annual series, one for snowmelt events and another for large ROS events: the maximum discharge, the event volume, and the event duration. Additional flood attributes were calculated for the annual series, the total volume, and the total duration of events; these calculations affect the annual snowmelt series since multiple events occur, but not the large ROS series as those events are rare.

Analysis of mixed populations of floods remains challenging. Technical reports describing early flooding events in the Bow Valley and in the Banff area provided clear evidence of nine large ROS events (1909, 1915, 1916, 1918, 1923, 1929, 1932, 2012, and 2013; see Table I for citations). Large floods occurred in the Bow River in 1879, 1897, 1902, 1915, 1929, and 1932 and lesser floods in 1916, 1923, 1933, 1948, and 1953 that were associated with heavy widely distributed rains (Armstrong *et al.*, 2009). Technical reports from the Department of the Interior and Dominion Water Power (Sauder, 1914; Whyte, 1914, 1916; Ford, 1924; Hoover 1929; Hoover and MacFarlane, 1932) provide evidence that these events were similar in scale and nature to the large ROS events of 2005, 2012, and 2013. Table I also includes large floods reported before streamflow data became available (1909). Procedures that automatically separate floods by type are desired. The large ROS events were confirmed by considering several aspects. In snowmelt-dominated peak flow years, the central ranges in Banff National Park contribute more to runoff than the front ranges and foothills (Pomeroy *et al.* 2016a); during mesoscale events such as 2013, relatively more runoff is contributed from the front ranges and foothills between Banff and Calgary. In 'normal' years, which are snowmelt-dominated, the Bow River at Banff contributes a greater proportion of the runoff at Calgary than would be estimated solely by the drainage area ratio (28%); deviations below this runoff ratio were used to identify events where more flows were being generated in the lower basin downstream of Banff. Heavy rainfall events, observed at Banff, identified periods where rainfall was in excess of 40 mm (larger than the daily spring snowmelt as identified by Pomeroy *et al.*, 2012) and three day rainfalls were in excess of 70 mm, suggesting a large-scale frontal source of rainfall that would cover the basin, rather than a small-scale convective storm that might only affect the area around the Banff rain gauge. Neither of these was sufficient to support identification of large ROS events on a consistent basis as temperature and antecedent snowpack also play significant roles (Fang and Pomeroy, 2016). For example, in 2005, there was a large rain event in Alberta that resulted in widespread flooding (Shook, 2016) and large amounts of rain occurred in Banff, yet the observed peak in the Bow River at Banff was relatively small (167 m^3/s; Table I).

All the analysis presented was performed by using 'R' (R Development Core Team, 2014). Non-parametric correlations (Kendall rank) were used to assess relationships between the climate system, burned area, and the flood attributes. Trend tests for annual and monthly series were performed by using Mann–Kendall test, a widely used non-parametric trend test by using 'Kendall' (McLeod, 2015). None of the flood attribute series exhibited significant autocorrelation. All significance testing was performed by using $p \leq 0.05$. Frequency analysis was performed by using peaks over threshold series using the package 'FAmle' and 'ismev'.

Records of fire occurrence and extent in Banff National Park were extracted from White (1985) and records obtained from Parks Canada (J. Park, personal communication). Event data are insufficient to relate the persistent effects of fire on the landscape as the effect of a fire persists beyond the year in which it occurs (e.g. Mahat *et al.*, 2015). A simple model of the effects of the fire was developed that consisted of two components, a direct effect period and a recovery period. The direct effect period reflects the time where the landscape effects of the fire continued and forest vegetation was largely removed from the landscape and soils may have been disturbed. The subsequent recovery period is assumed to be a linear transition from affected to 'undisturbed' forested conditions. This model does not address the intended impacts of prescribed burns, which include alteration of forest species succession and the conversion of forest to grassland in the driest sites. A direct effect period of 5 years, followed by a recovery period of 10 years, was used based upon the literature (Johnson and Fryer, 1987; Ireland and Petropoulos, 2015; Mahat *et al.*, 2015; Springer *et al.*, 2015).

Table I. Large rain-on-snow events in the Bow River at Banff

Date	Maximum daily mean flow (m^3/s)	Description	Banff Rainfall (mm)	Banff 3-day rainfall (mm)	Reference
1879		*Large flood in Bow Valley*			Dawson, 1886; Sauder, 1914
1884		*Largest flood in 100 years* [*Dawson*]			Dawson, 1886; Sauder, 1914
1897		*Widespread rain 3“ in 3 days*			Sauder, 1914
1902		*Bountiful rainfall Calgary 1.78“ (45.2 mm) in 1 day*	*31.8*	*83.1*	Sauder, 1914
09/06/1909	314	Largest measured (Ford, 1924); warm temperatures	10.7	13.2	Sauder, 1914; Ford, 1924
26/06/1915	236	Extensive heavy precipitation	50	66.3	Whyte, 1916
16/06/1916	309	Exceptionally heavy precipitation	10.4	23.6	Ford, 1924
09/06/1918	345	Rain on snow	10.7	11	Ford, 1924
05/06/1923	377	A series of four storms centred on mountains/foothills; new maximum stage, possibly in excess of any previous. Only one of these affected the Bow River at Banff, the others were observed in the Bow River at Calgary as progressively higher peaks	30.7	67.6	Ford, 1924; Hoover, 1929
01/06/1929	215	Torrential rains	46.2	64	Hoover, 1929
01/06/1932	279	Heavy rains on large snow pack: new maximum on Spray but not in Bow at Banff	33.8	70.9	Hoover and MacFarlane, 1932
18/06/2005	167*	Large rain event affected a north south band across the foothills, but not the Bow River at Banff	55.4	107	Shook, 2016
05/06/2012	332	Widespread heavy rainfall	47.3	71.4	
06/06/2013	490	Spring snowmelt coupled with extreme rainfall	59.9	90.9	Milrad *et al.*, 2015; Pomeroy *et al.*, 2016a,b

The events prior to 1909 are included based upon published material. Subsequent to 1909 the combination of large flood magnitude, heavy rain fall at Banff, and documenting literature served to identify nine events between 1909 and 2014.

*Not considered a large rain-on-snow event in this study.

RESULTS

The entire daily data set from the Bow River at Banff, including periods of reported ice cover, is shown as a raster plot (Figure 2). The largest discharge peaks occur between days 150 and 200 throughout the record, and the peaks are generally early in the high-flow period, rather than later in the year. In most years, ice cover remains on the river until late March or early April, generally around day 100 (Figure 2). Annual streamflow patterns appear to be consistent over the period of published record between 1909 and 2012.

Analysis was performed on the series of 349 individual events in excess of the 90th quantile, and for trends and frequency analysis, these were reduced to three series, one for all events, one for snowmelt events, and one for large ROS events. The results for the individual events are presented first followed by those for the annual series.

Individual events in excess of Q90

The time series of the flood attributes of the 349 individual events above the 90th quantile of mean daily discharge from the Bow River at Banff is shown in Figure 3. The large ROS events between 1909 and 2015 listed in Table I are shown as squares, whilst all other events are shows as circles. Colour in Figure 3 indicates the month in which the event started, clearly indicating that all large events and 92% of the events greater that Q90 occur in May, June, and July (20, 47, and 26%, respectively), whilst some smaller magnitude events do occur in August (7%) and September (<1%). The identified ROS events (Table I) dominate the events that exceed 300 m^3/s (Figure 3a) and occur in two separate groups, one ending in 1932 and the other in 2012 and 2013. The time series of event volumes (Figure 3b) shows that large-volume events occur most frequently in June and July and that the large-magnitude ROS events are not the largest-volume events, but similar to other events. The large ROS events also have similar durations to other events (Figure 3c). Snowmelt event attributes are highly correlated (0.77–0.95, all $p \leq 0.05$), whilst for ROS only, volume and duration are correlated (0.91, $p \leq 0.05$); however, the number of ROS events being compared is small.

Booth *et al.* (2006) suggested that plotting flood event duration *versus* magnitude *versus* timing (Figure 4) is

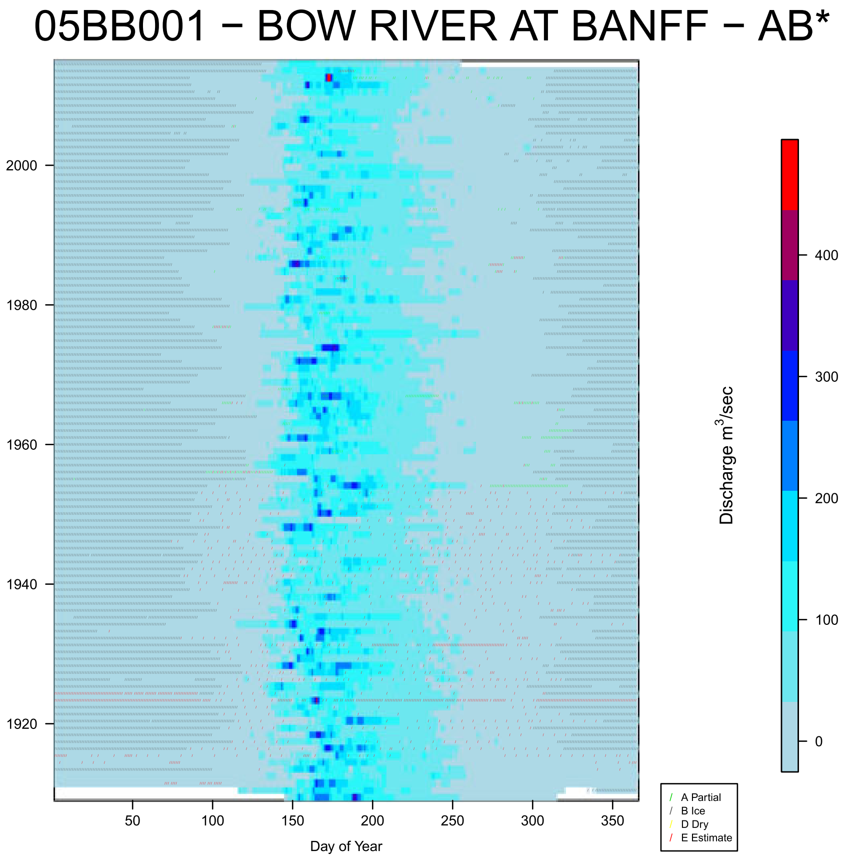

Figure 2. Raster plot of daily streamflow observations in the Bow River at Banff 05BB001 from 1909 to 2012. Gray bars indicate the reported presence of ice cover

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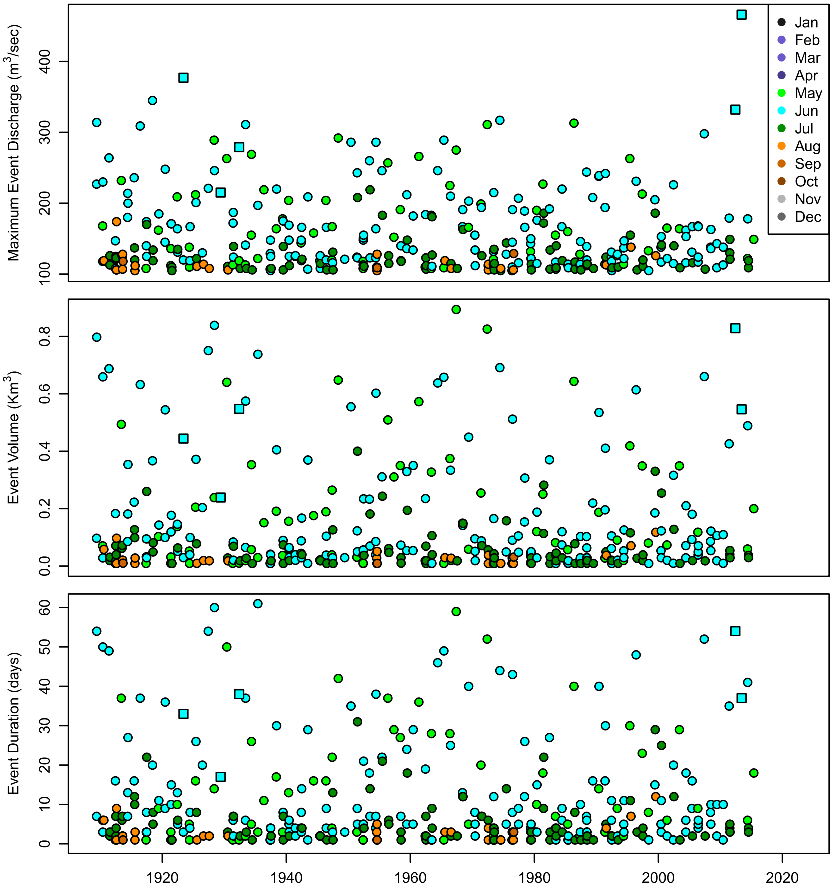

Figure 3. Attributes of events in excess of 90th percentile (in excess of 104 m3/s) for the Bow River at Banff 05BB001, (a) maximum discharge, (b) . event volume, and (c) duration. The solid squares indicate major rain-on-snow events. Colour indicates the month in which the event began. Note that 92% of the events begin in May, June, and July

useful for separating flood types using time and magnitude thresholds. While Figure 4 is clearly sensitive to the selection of a threshold, it does demonstrate the range of differences in the types of events. Here, the ROS events are of the highest magnitude and of similar duration and timing to the largest snowmelt events, but large snowmelt and ROS event magnitudes overlap. Many events with short durations and small magnitudes are shown in Figure 4; the largest magnitude events have durations between 7 and 40 days and occur in May and June. August and September events have durations between 3 and 15 days and are of lower magnitude.

The results presented here compare time series of climate indices, area affected by fire, and flood attributes and also tests for trend. Figure 5 shows the four annual climate indices, AMO, NAO, SOI, and PDO, for each flood event in the individual series.

Two climate system features, PDO and SOI, are reported to have effects on climate and hydrology in western Canada and are explored in more detail in the succeeding texts. Plotting the relative magnitude, volume, and duration for individual snowmelt and ROS events as a function of PDO and SOI is shown in Figure 6a–c. In Figure 6 the ROS events are shown as squares; these events predominately occur during negative values of the PDO and neutral (La Nada) values of SOI.

Annual events in excess of Q90

The annual observed area burned in individual years and an estimated area affected by forest fires are shown in Figure 7. These estimates are modelled using the premise that a fire has 5 years of direct hydrological impact, followed by a recovery period of 10 years. Forests in Banff National Park are restricted to the valley bottoms and slopes (Figure 1) and occupy only about 44% of the Park area (Van Wagner *et al.*, 2006). Large wild fires were common prior to 1940; after 1985, prescribed fires occurred. The management strategy of fire suppression during the years from 1930 to 1985 is obvious in the observed fires and modelled affected area. The modelled affected area exceeds 10% of the forested area of the park before 1900 and reached that level again around 2010.

Large floods in the Bow River at Banff represent a mixture of processes (Pomeroy *et al.* 2016a). Identifica-

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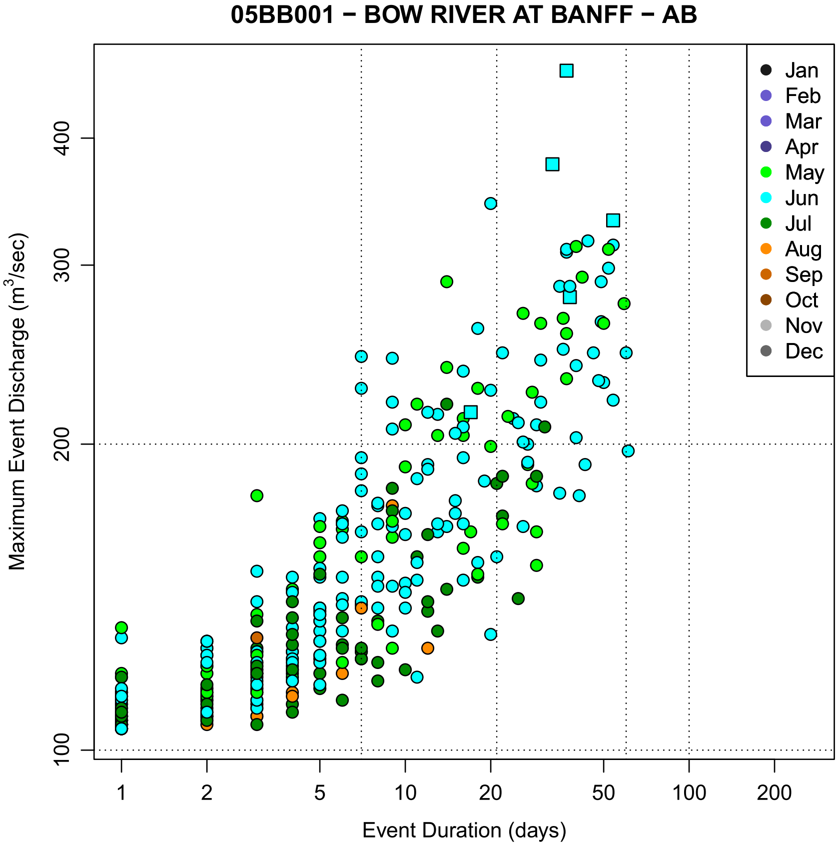

Figure 4. Seasonal distribution of peaks in excess of 90th percentile for different durations for the Bow River at Banff. The solid squares indicate major rain-on-snow events

tion of ROS events using published reports (Table I) and meteorological records suggested that nine events have occurred during the period where streamflow data were available. Published records (Table I) indicate that four events occurred before streamflow records were available. This indicates that 11 such events occurred between 1879 and 1932 and another two in 2012 and 2013, suggesting that these events are patchy in time and the probability of this type of an event is not random.

Non-parametric correlations between years, the climate indicates, burned area, and the annual flood attributes are shown in Table II. The bold values in larger font are significant at $p \leq 0.05$ and the number of degrees of freedom varies widely due the availability of data (e.g. climate indices) and the occurrence of floods (e.g. only 9 years have ROS events). There are many significant correlations for similar generating processes amongst the flood attributes such as event maximum, volumes, and duration in the lower right portion of the table. Some of the high degree of correlation amongst flood attributes indicates that these attributes are not independent of each other. Similar correlations were obtained for the individual peak events and are not repeated here. Significant correlations between years and flood attributes are generally similar to those found by using the Mann–Kendall trend test (next section). There are significant correlations amongst the atmospheric indices, specifically between AMO and NAO and between SOI and PDO. There are also significant correlations between climate indices and burned area, which are spurious as the pattern of burned area is clearly a product of fire suppression and prescribed burns and not a response to the climate system. The only significant correlation between flood attributes and the climate system was snowmelt duration with the PDO; this coefficient is very low, and the significance is due to the large sample size and not expected to be hydrologically important. There were no significant correlations between flood attributes and burned area – positive correlations would be expected given that the snow process changes associated with canopy removal (Pomeroy *et al.*, 2012).

Trends in flood attributes for the combined series and separate snowmelt and ROS events are shown in Table III and Figure 8. While there are significant declining trends in maximum peak discharge and total event volume when the entire series of annual events is considered, no significant trends were detected for either the separated snowmelt series or the ROS series. As shown in

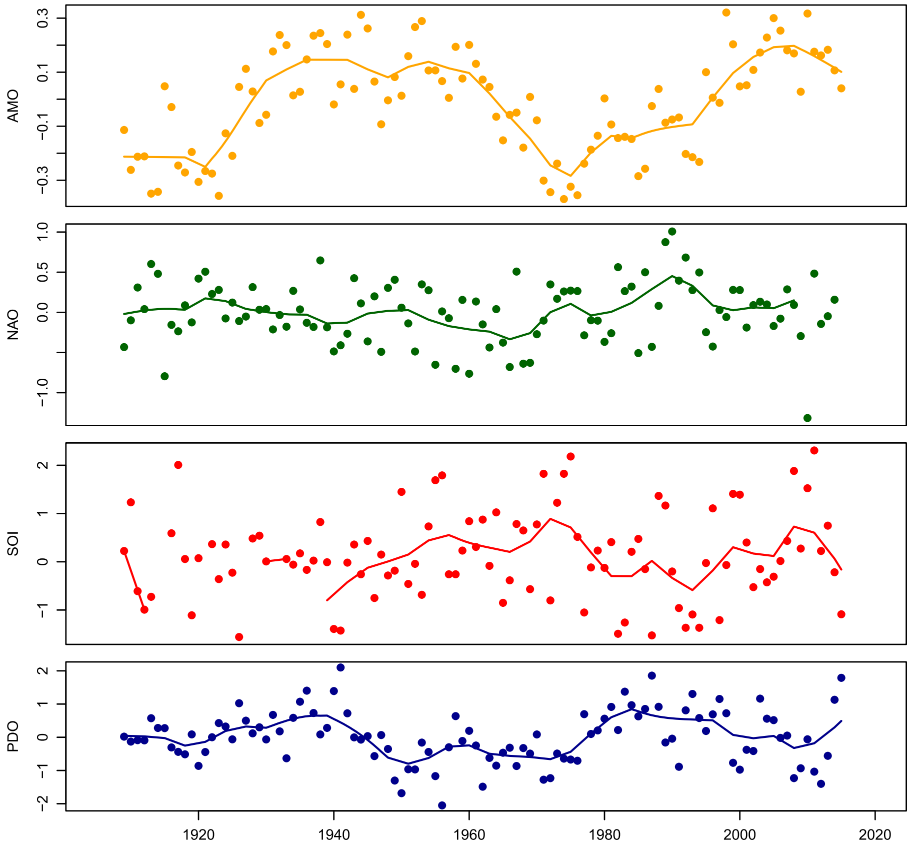

Figure 5. Annual climate indices for individual flood events in excess of the Q90 threshold

Figure 8a, a statistically significant decrease in the combined maximum flood was found for the period of record, but not for the separated snowmelt or ROS series. Similarly, in Figure 8b, there is a significant deceasing trend in the combined series of total event volume, but not in either the snowmelt or ROS series. There were no trends in the total annual duration of events significant at $p \leq 0.05$ (Figure 8c).

Several different distributions were fit to the snowmelt and ROS peak series; Figure 9 shows the diagnostic plots using the generalized extreme value distribution. Similar fits were obtained by using other distributions such as the Log Pearson Type III, but are not shown. The differences between the ROS and snowmelt series are clear from the difference between the maximum likelihood estimates of location (179.6 *vs* 287.8), shape (44. *vs* 421.5), and scale (66.8 *vs* 88.8) between snowmelt and large ROS events as reflected in return period plots (Figure 9). These are adequate fits for the current purpose, but the fact that the largest observations in each series deviate far from the fitted line suggests that caution must be used by using these distributions to describe extreme events. There are large differences in the location, shape, and scale estimates; the return periods with a probability of 0.01 for a snowmelt event are estimated to be ~340 m^3/s, whilst those for a ROS event would be ~540 m^3/s. More importantly, three of the nine largest ROS events observed in the past 100 years exceed 340 m^3/s. Run tests indicate that the ROS events are not random over the period of record ($p < 0.05$).

DISCUSSION

Statistical analysis of hydrological time series generated by mixed processes continues to be a challenge. This has been clear since early work on frequency analysis (Moran, 1957; Waylen and Woo, 1982, 1983; Woo and Waylen, 1984). Whilst most studies of flood series focus on the annual maximum series, all events greater than a threshold are considered here for a discharge series, which is more than 100 years in length.

Burn and Whitfield (2016) showed than many annual maximum series in Canada, including the Bow River at Banff, were showing declining trends. The trend tests in Figure 8 and Table III for the combined series show similar results to those of Burn and Whitfield (2016). Separating the series of peaks based on generating process results in neither series having a significant

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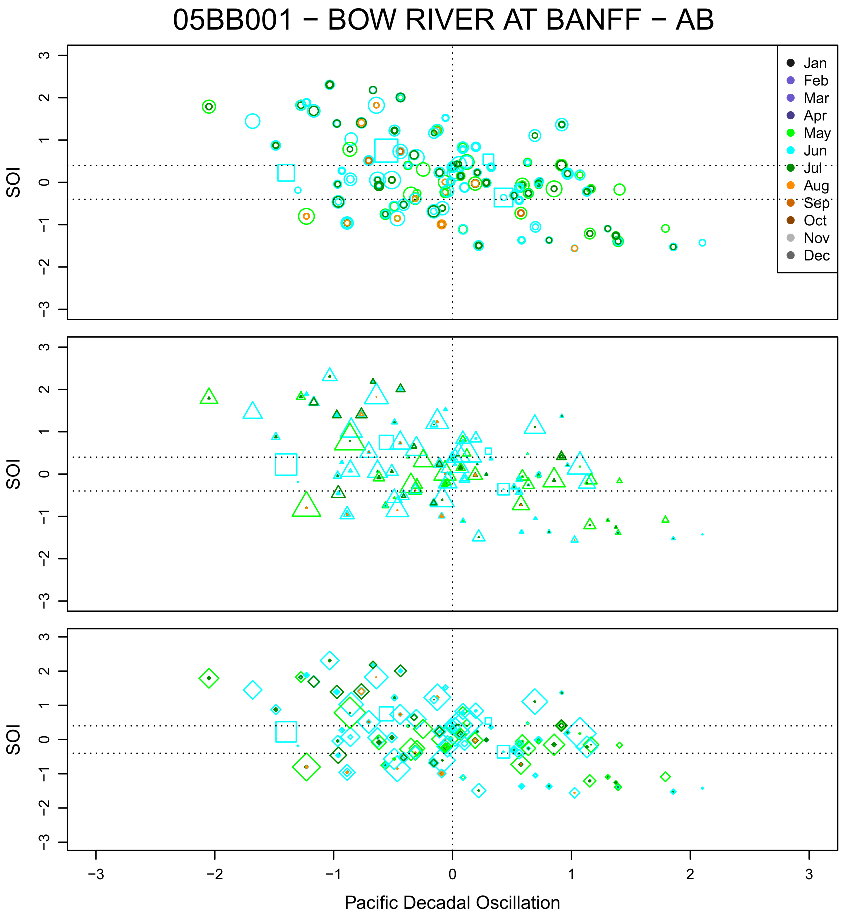

Figure 6. Timing and magnitude, volume, and duration of individual flood events in relation to SOI and PDO. The size of the symbol is relative to the maximum value. The squares indicate the large ROS events. Colour indicates the month in which the event began

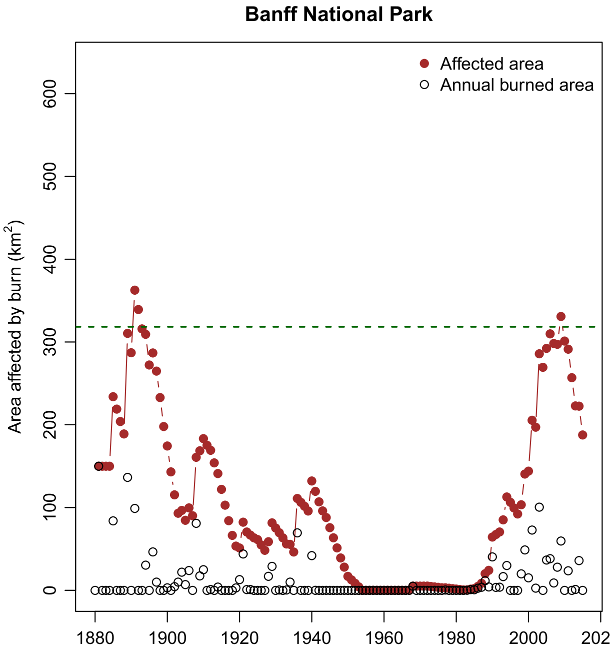

Figure 7. Reported forest fires areas and modelled affected area of burn. The horizontal dotted line indicates 10% of the total area of Banff National Park

trend for any of the attributes considered. Whilst the importance of this separation for frequency analysis has long been known, it appears to apply also to trend analysis. A methodology where streamflow records themselves could be used to separate floods based upon their generating processes is sorely needed. Studies of flood series that are unable to separate flood events based on mixed generating processes could be problematic as noted by Pomeroy *et al.* (2016a,b).

From the perspective of frequency analysis, the properties of the two series of floods are different. Flood frequency analysis of series separated based on runoff generation process demonstrates the differences in properties of the two series and the disproportional number of events of different types. Considering these separately, the statistical distributions are very different and estimates of return periods differ substantively. For the snowmelt series, the 0.01 event would be ~340 m^3/s whilst six of the nine large ROS events in the past 106 years exceed that amount. Clearly, the snowmelt series does not inform estimation of large floods. But

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Table II. Kendall rank correlations amongst the event values for years, climate system, burned area, and snowmelt (snow) and rain-on-snow (ROS) flood attributes for the Bow River at Banff (05BB001) between 1880 and 2013

	Year	AMO	NAO	SOI	PDO	Burned Area	Snowmelt event maximum	Snowmelt event volume	Snowmelt event duration	ROS event maximum	ROS event volume	ROS event duration
Year												
AMO	**0.13**											
NAO	0.17	−**0.23**										
SOI	0.04	0.03	−0.02									
PDO	0.02	0.03	−0.08	−**0.31**								
Burned area	−0.05	**0.11**	0.09	−**0.08**	**0.11**							
Snowmelt event maximum	−0.02	0.02	0.02	0.04	−0.05	−0.01						
Snowmelt event volume	0.01	0.03	0.03	0.04	−0.07	0.00	**0.77**					
Snowmelt event duration	0.01	0.03	0.04	0.03	−**0.08**	0.00	**0.73**	**0.95**				
ROS event maximum	*0.28*	−*0.17*	*0.28*	−*0.29*	−*0.44*	*0.22*	—	—	—			
ROS event volume	*0.11*	*0.11*	−*0.22*	*0.00*	−*0.39*	*0.28*	—	—	—	*0.28*		
ROS event duration	*0.17*	*0.17*	−*0.17*	*0.05*	−*0.34*	*0.23*	—	–	—	*0.23*	***0.91***	

Bold values indicate significance at $p \leq 0.05$. There are different degrees of freedom due to different amounts of available data. Italicized and underlined values have inaccurate probabilities since $n < 10$.

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Table III. Summary of trend results for flood attributes

	All data		Snowmelt		Rain-on-snow	
	Tau	*p*	Tau	*p*	Tau	*p*
Maximum peak discharge	**−0.163**	**0.01**	−0.083	0.22	−0.004	0.95
Total event volume	**−0.139**	**0.03**	−0.069	0.30	0.111	0.75
Total event duration	−0.123	0.06	−0.058	0.39	0.000	1.00

Statistically significant values are bold and underlined. These series are presented in Figure 8.

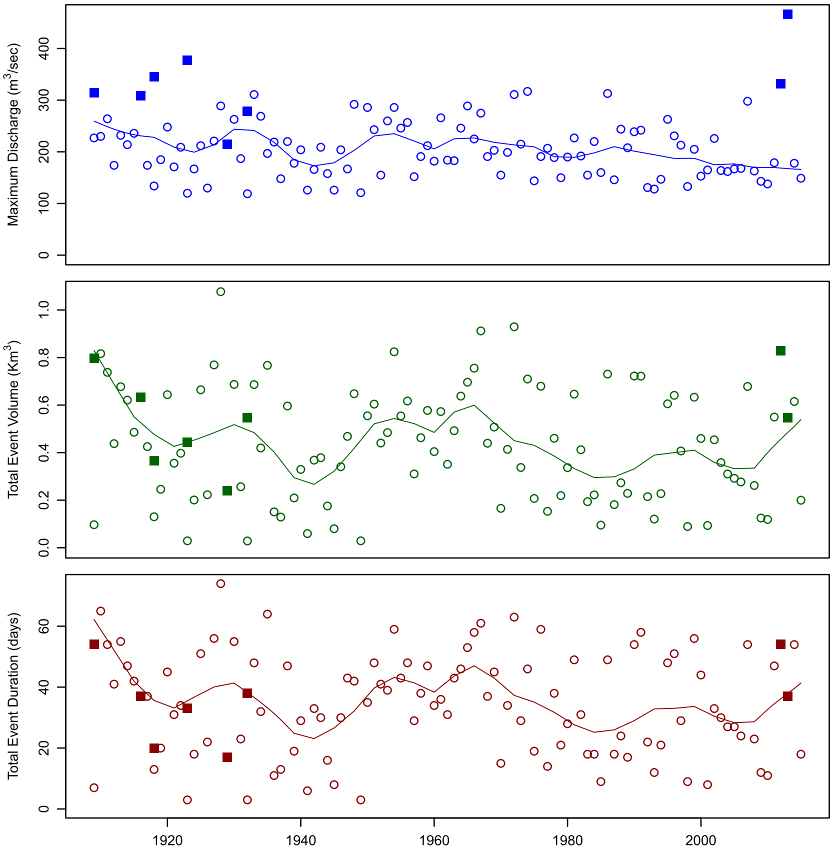

Figure 8. Annual maximum, total event volume, and total event duration of snowmelt and rain-on-snow events that exceed the 90th quantile. The line is a lowess fit to the combined series of events

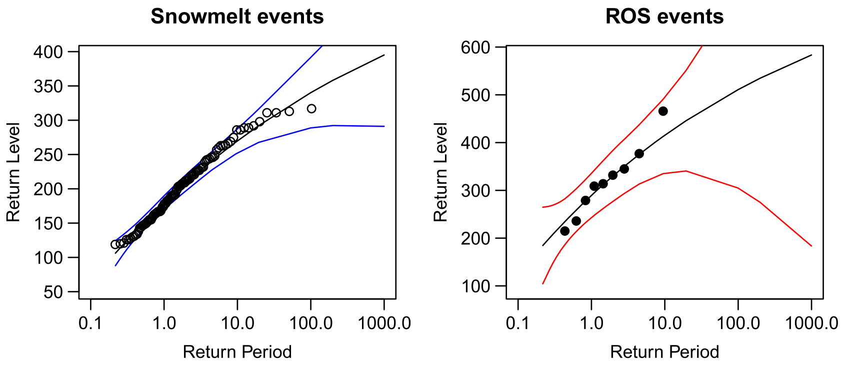

Figure 9. Within group Return level plots using GEV for (a) snowmelt events and (b) rain-on-snow events for the Bow River at Banff. The black line is the GEV fit to the points, and the blue lines are the 95% confidence intervals. The return level is in m^3/s, and the return period is in years

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the sample size of ROS is so small that estimation of large floods from this series is highly uncertain.

Mixed populations such as found here were discussed by Klemeš (1982) who argued that the concept of mixed floods is meaningful if physically justified and the subgroups can be separated on physical evidence. Waylen and Woo (1982) examined the problem of differences between rainfall and snowmelt generated floods; Hirschboeck (1987, 1988) examined flood event hydroclimatology and linked flood types to synoptic atmospheric circulation mechanisms. The more frequent snowmelt events do not produce, the largest floods in the Bow River at Banff; ROS events whilst less common impose a much larger risk. Large ROS events occur in about 8% of the years of the 105-year observed streamflow record and have a much large magnitude for similar return periods. Dealing statistically with two flood types is complicated from either trend or frequency perspectives. Further complicating matter is the fact that over time, the ROS events are not random. New approaches will be required to address frequency analysis for mixtures of flood events where the occurrence of events is not random but has some unknown form of time structure. Using a threshold of Q90, the 90th quantile was chosen to ensure that at least one event occurred in each year and resulted in a total of 349 individual events where the flow exceeded 104 m^3/s for at least one day. Using this threshold, the peak magnitude, volume of water, and duration during the event could also be determined. Whilst the three attributes are not statistically independent, they provide additional information about the types of peak flow events. These events were separated into two groups: a ROS group which was identified based on historical records as being similar to the 2012 and the 2013 event reported in Milrad *et al.* (2015). Pomeroy *et al.* (2016a), and Liu *et al.* (2016) and a group where snowmelt is the dominant mechanism associated with the events. The snowmelt group of events does, however, include short-duration events that may be caused by other mechanisms. The plot of duration *versus* magnitude proposed by Booth *et al.* (2006) and shown as Figure 4 is a useful method for considering a large group of events such as is available here; however, it does not provide an adequate separation by runoff generation type as was reported by Booth *et al.* (2006). In the Bow River, more mechanisms are involved in generating peaks than in Booth *et al.* (2006), where peak events were predominantly rainfall in origin. Large events in the Bow River at Banff, greater than 200 m^3/s, have durations between 7 and 70 days, and the largest of these have durations between 21 and 70 days and exceed 300 m^3/s. This is a substantial spread from any well-defined peak-duration curve.

Correlations of attributes describing annual and event flood peaks with those describing the climate system and burned area in the park showed similar null results. Only snowmelt duration was significantly correlated (negatively) to the PDO. ROS events were not significantly correlated to any climate system feature, likely the result of a small sample size of only nine events. The plot of flood types and the magnitude against SOI and PDO (Figure 5) show that snowmelt floods during the positive PDO tend to have smaller magnitudes and volumes and shorter durations than those during negative PDO, but these are not significant correlations. ROS events tend to occur mostly during negative PDO and neutral SOI as opposed to during El Niño or La Niña, but again not significantly. There is considerable scatter and lack of statistical significance to these associations, suggesting that only general remarks rather than predictions or conclusions are possible.

Snowmelt event maxima and total volume were found to be not correlated to the modelled burned area in the basin. This statistical finding is incompatible with the results of decades of research on forest snow hydrological processes in this region and similar environments (Golding and Swanson, 1978; Troendle and Leaf, 1981; Swanson and Golding, 1982; Swanson *et al.*, 1986; Hetherington, 1987; Macdonald *et al.*, 2003; Ellis *et al.*, 2011, 2013; Pomeroy *et al.*, 2012). Most observational literature suggests that a result of forest fires is an increase in runoff (Moody and Martin, 2001; Neary *et al.*, 2005). Such contrary results are most likely due to the small proportion to the total forested area affected (<10%). Harder *et al.* (2015) and Pomeroy *et al.* (2012) show that larger proportions of forest cover need to be disturbed before impacts can be detectable in streamflow regimes because much runoff in the Canadian Rockies is produced in alpine zones above the forest cover. Fang and Pomeroy (2016) modelled source areas for runoff production in Marmot Creek under different antecedent condition scenarios and found for many flood conditions; forest cover is important but impacts of forest disturbance are greatly magnified when the soil as well as the canopy is disturbed. The light soil disturbance of many wildfires and artificial fires and the small area of the basin affected by fire were not likely to result in any detectable impact on the streamflow regime.

In the Bow River at Banff, large ROS events were frequently reported prior to 1932 including a number before streamflow records began in 1909 (Table I). It is fortuitous that various records and histories regarding the Bow Valley exist as far back is they do, largely due to the ongoing importance of the valley for transportation with the building of the Canadian Pacific Railway in the 1880s and for conservation and tourism with the creation of Canada's first National Park Preserve at Banff in 1882

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and the expansion of the Rocky Mountain National Park (later Banff National Park). Without these records it would impossible to identify and separate such events. This limits the potential to expand this study as climate and historical records that were used to identify these ROS events do not exist for other places in Western Canada.

The clustering in time of ROS events is a particularly interesting observation in this streamflow series as it suggests the possibility of changes in the frequency of winters with deep, late-lying snowpacks or in the frequency of the large-scale systems that drive these large-scale ROS events or both. A detailed elevational analysis of hydrometeorological changes in the nearby Marmot Creek Basin over 50 years by Harder *et al.* (2015) found that temperatures had increased at all elevations and whilst low-elevation snowpacks had declined by 50%, high-elevation snowpacks showed no trend. Annual precipitation also showed no trend but there was greater clustering of multiple day precipitation events in spring and total spring precipitation over time at high elevations. The clustering of precipitation in multiple day events was found to be common in the Canadian Prairie Provinces over the last century (Shook and Pomeroy, 2012). The declining low-elevation snowpacks might help explain the declining trend in peak and volume of all events, except that Bow River snowmelt peaks and volumes have not been declining. The increase in large spring precipitation events over the last 50 years might be manifest in the return of large-scale systems that caused flooding in 2012 and 2013, but the Marmot Creek record does not go back far enough to help interpret or diagnose the decline in early 20th century large floods, and in general, this trend runs counter to the declining trend in peak and volume. Harder *et al.* (2015) found no trend in Marmot Creek peak flows and flow volumes at various elevations over time, suggesting a remarkable hydrological resilience to climate and land cover change in that small basin ($<10\,\text{km}^2$). It is very interesting that at least for peak flows, characteristics of this resiliency scale up to the $2210\,\text{km}^2$ Upper Bow River basin. There may be an association between warming temperatures and declining peaks and volumes as higher temperatures are associated with drier and less snow-covered antecedent conditions (Fang and Pomeroy, 2016; Rood *et al.*, 2016). It is suggested that further research looks for pattern changes both in space and in time of the meteorological event and couple that with models addressing long-term variations in snow accumulation and soil moisture. This approach was found to be fruitful on the North American coast events when considering the Pineapple Express (Dettinger, 2011). How would cycles of snow accumulation, perhaps modulated by the PDO, interact with an atmospheric regime where mesoscale precipitation events were becoming more common over a relatively short time period? Ntegeka and Willems (2008) examined rainfall events in a rainfall record of similar length (107 years) showing significant changes in rainfall quantiles between periods that persisted for 10 to 15 years indicating clustering of large events. It would seem that studies of the type conducted by Ntegeka and Willems (2008) are rare.

CONCLUSIONS

Trends in annual floods in the Bow River at Banff using the annual maxima series show significant declining trends in magnitude and volume, but not duration. These results are similar to those reported by Burn and Whitfield (2016). As is the case for flood frequency analysis, when events can be separated by generating process, the results are quite different; no trends in flood attributes were found when snowmelt peak and large ROS series were tested separately. This presents an important quandary for those responsible for risk management of engineering structures and public safety as it necessarily changes how one needs to think about flood processes in relation to the existing information about floods. There has long been recognition that records may not be stationary, and there are numerous papers reporting on trends differing between different time periods, but when faced with multiple flood-generating processes that change in proportion over time, existing methods are clearly inadequate and unreliable.

The frequency analysis of the two types of events showed important differences. Large ROS events are rare and important, occurring in less than 8% of years but generating streamflows of great consequence. The peak streamflow estimated from the snowmelt series for a 0.01 (1:100 years) probability event has a probability of ~0.3 (1:3 years) for large ROS events. Clearly, more knowledge of the occurrence of these events in space and time is important.

As would be expected for different measures of similar events, snowmelt flood attributes were found to be highly correlated amongst themselves, as were ROS flood attributes. Burned area was not significantly associated with any snowmelt or ROS descriptor, likely due to the small burned area in the basin. No snowmelt flood attributes were significantly correlated to PDO or other climate system indices, except flood duration to the PDO; ROS attributes were not correlated with any of the other variables. The statistically significant trend for declining flood peaks and volumes broke down when floods were stratified into snowmelt and ROS events, suggesting the inadequacy of current statistical techniques when applied to mixed process events. The general lack of association

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with climate index or burned area and mixed results for trends over time suggests a remarkable resiliency to the Upper Bow River, something never identified for larger-scale river basins in western Canada, but found for small headwater catchments. This upscaling of hydroclimatic and forest fire disturbance resiliency has major implications for climate change and land cover change mitigation policies in the region.

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REFERENCES

Armstrong C, Evenden M, Nelles HV. 2009. *The River Returns: An Environmental History of the Bow*. McGill-Queens University Press: Montreal PQ.

Binnema T, Niemi M. 2006. 'Let the line be drawn now': wilderness, conservation, and the exclusion of aboriginal people from Banff National Park in Canada. *Environmental History* **11**: 724–750.

Booth EG, Mount JF, Viers JH. 2006. Hydrologic variability of the cosumnes river floodplain. *San Francisco Estuary and Watershed Science* **4**: Article 2. 21pp.

Brimley B, Cantin JF, Harvey D, Kowalchuk M, Marsh P, Ouarda TMBJ, Phinney B, Pilon P, Renouf M, Tassone B, Wedel R, Yuzyk T, et al. 1999. *Establishment of the Reference Hydrometric Basin Network (RHBN) for Canada*. Environment Canada: Ottawa; 41pp.

Budikova D, Nkemdirim LC. 2005. Relative changes in consistency of winter surface air temperature during ENSO events across western Canada. *The Canadian Geographer* **49**: 81–99.

Burn DH. 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River basin. *Journal of Hydrology* **352**: 225–238.

Burn DH, Whitfield PH. 2016. Changes in floods and flood regimes in Canada. *Canadian Water Resources Journal* **41**: 139–150.

Burn DH, Hannaford J, Hodgkins GA, Whitfield PH, Thorne R, Marsh TJ. 2012. Hydrologic Reference Networks II. Using Reference Hydrologic Networks to assess climate driven changes in streamflow. *Hydrological Sciences Journal* **57**: 1580–1593.

Byrne AR. 1964. Man and landscape change in the Banff National Park Area before 1911. University of Alberta.

Chanasyk DS, Whitson IR, Mapfumo E, Burke JM, Prepas EE. 2003. The impacts of forest harvest and wildfire on soils and hydrology in temperate forests: a baseline to develop hypotheses for the Boreal Plain. *Journal of Environmental Engineering and Science* **2**: S51–S62.

Comeau LEL, Pietroniro A, Demuth MN. 2009. Glacier contribution to the North and South Saskatchewan Rivers. *Hydrological Processes* **23**: 2640–2653.

Dawson GM. 1886. *Preliminary report on the physical and geological features of that portion of the Rocky Mountains between Latitude 49° and 50°30′, Geological and Natural History Survey of Canada Montreal*.

Day RJ. 1972. Stand structure, succession, and use of southern Alberta's Rocky Mountain forest. *Ecology* **53**: 472–478.

Déry SJ, Wood EF. 2005. Decreasing river discharge in Northern Canada. *Geophysical Research Letters* **32**: DOI:10.1029/2005GL022845

Dettinger M. 2011. Climate change, atmospheric rivers, and floods in California - a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association* **47**: 514–523.

Enfield DB, Mestas-Nuñez AM, Trimble PJ. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* **28**: 2077–2080.

Ellis CR, Pomeroy JW, Link TE. 2013. Modeling increases in snowmelt yield and desynchronization resulting from forest gap-thinning treatments in a northern mountain headwater basin. *Water Resources Research* **49**: DOI:10.1002/wrcr.20089

Ellis CR, Pomeroy JW, Essery RLH, Link TE. 2011. Effects of needleleaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains. *Canadian Journal of Forest Research* **41**: 608–620. DOI:10.1139/X10-227

Fang X, Pomeroy J. 2016. Impact of antecedent condition on simulations of a flood in a mountain headwater basin. *Hydrological Processes*, DOI: 10.1002/hyp.10910.

Feunekes U, Van Wagner CE. 1995. *A Century of Fire and Weather in Banff National Park*. Park Canada: Banff; 11.

Fleming SW, Sauchyn DJ. 2013. Availability, volatility, stability, and teleconnectivity changes in prairie water supply from Canadian Rocky Mountain sources over the last millennium. *Water Resources Research* DOI:10.1029/2012WR012831:11

Fleming SW, Whitfield PH. 2010. Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and Southeast Alaska. *Atmosphere-Ocean* **48**(2): 122–131.

Fleming SW, Whitfield PH, Moore RD, Quilty EJ. 2007. Regime-dependant streamflow sensitivities to Pacific climate modes across the Georgia-Puget transboundary ecoregion. *Hydrological Processes* **21**: 3264–3287.

Ford JD. 1924. Floods in the southern parts of Alberta and Saskatchewan during 1923. Department of the Interior. Dominion Water Power Branch. 85pp.

Fortier C, Assani AA, Mesfioui M, Roy AG. 2011. Comparison of the interannual and interdecadal variability of heavy flood characteristics upstream and downstream from dams in inversed hydrologic regime: case study of the Matawin River (Québec, Canada). *River Research and Applications* **27**: 1277–1289.

Golding DL, Swanson RH. 1978. Snow accumulation and melt in small forest openings in Alberta. *Canadian Journal of Forest Research* **8**: 380–388.

Harder P, Pomeroy JW, Westbrook CJ. 2015. Hydrological resilience of a Canadian Rockies headwaters basin subject to changing climate, extreme weather, and forest management. *Hydrological Processes* DOI:10.1002/hyp.10596

Hart EJ. 1999. *The Place of Bows: Exploring the Heritage of the Banff-Bow Valley. Part I to 1930*. EJH Literary Enterprises: Banff, AB.

Hart EJ. 2003. *The Battle for Banff: Exploring the Heritage of the Banff-Bow Valley: Part II, 1930–1985*. EJH Literary Enterprises: Banff, AB.

Hetherington ED. 1987. The importance of forests in the hydrological regime. In *Canadian Aquatics Resources Vol. 215*, Healey MC, Wallace RR (eds). Canadian Bulletin of Fisheries and Aquatic Sciences, Fisheries and Oceans Canada: Ottawa, Canada; 179–211.

Hirschboeck KK. 1987. Hydroclimatologically-defined mixed distributions in partial duration flood series. In *Hydrologic Frequency Modeling*, Singh VP (ed). Reidel: Dordrecht, NETH; 199–212.

Hirschboeck KK. 1988. Flood hydroclimatology. In *Flood Geomorphology*, Baker VB, Kochel RC, Patton PC (eds). Wiley: New York NY; 27–49.

Holland WD. 1982. *Ecological Land Classification in Banff and Jasper National Parks. Canadian Forestry Service*. ABE: Edmonton; 18.

Hoover OH. 1929. Floods in Southern Alberta and Saskatchewan during 1929. Canada Department of the Interior. *Dominion Water Power and Reclamation Service*. 89pp.

Hoover OH, MacFarlane WT. 1932. Floods in Southern Alberta during 1932. Canada Department of the Interior. *Dominion Water Power and Hydrometric Bureau*. 73pp.

Hopkinson C, Young GJ. 1998. The effect of glacier wastage on the flow of the Bow River at Banff, Alberta, 1951–1993. *Hydrological Processes* **12**: 1745–1762.

Hurrell JW, Kushnir Y, Visbeck M. 2001. The North Atlantic Oscillation. *Science* **291**: 603–604.

Ireland G, Petropoulos GP. 2015. Exploring the relationship between post-fire vegetation regeneration dynamics, topography and burn severity: a case study from the Montane Cordillera ecozones of western Canada. *Applied Geography* **56**: 232–248.

Janz B, Storr D. 1977. *The Climate of the Contiguous Mountain Parks: Banff Jasper Yoho Kootenay*. Parks Canada: Toronto.

Johnson EA, Fryer GI. 1987. Historical vegetation change in the Kananaskis Valley, Canadian Rockies. *Canadian Journal of Botany* **65**: 853–858.

Johnson EA, Wowchuk DR. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Canadian of Journal Forest Research* **23**: 1213–1222.

Klemeš V. 1982. Empirical and causal models in hydrology. In *Scientific Basis of Water-Resource Management*. National Academy Press: Washington DC; 95–104.

Liu A, Mooney C, Szeto K, Terriault JM, Kochtubajda B, Stewart RE, Boodoo S, Goodson R, Li Y, Pomeroy J. 2016. The June 2013 Alberta Catastrophic Flooding Event: Part 1 – climatological aspects and hydrometeorological features. *Hydrological Processes* DOI:10.1002/hyp.10906

Luckman BT. 1998. Landscape and climate change in the central Canadian Rockies during the 20th century. *Canadian Geographer* **42**: 319–336.

Macdonald JS, Beaudry PG, MacIsaac EA, Herunter HE. 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. *Canadian Journal of Forest Research* **33**: 1397–1407. DOI:10.1139/X03-110

Mahat V, Anderson A, Silins U. 2015. Modelling of wildfire impacts on catchment hydrology applied to two case studies. *Hydrological Processes* **17**: 3687–3698.

Mantua NJ, Hare SR. 2002. The Pacific Decadal Oscillation. *Journal of Oceanography* **58**: 35–44.

McLeod AI. 2015. Package 'Kendall'. http://www.stats.uwo.ca/faculty/aim

Milrad S, Gyakum J, Atallah E. 2015. A meteorological analysis of the 2013 Alberta Flood: antecedent large-scale flow pattern and synoptic-dynamic characteristics. *Monthly Weather Review* **143**: 2817–2841.

Moody JA, Martin DA. 2001. Post-fire, rainfall intensity–peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* **15**: 2981–93.

Moran PAP. 1957. The statistical treatment of flood flows. *Transactions American Geophysical Union* **38**: 519–523.

Neary DG, Ffolliott PF, Lansdsberg JD. 2005. Fire and streamflow regimes. In: *Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. RMRS-GTR-42*. 107–118.

Nelson JG, Byrne AR. 1966. Man as an instrument of landscape change: fires, floods, and national parks in the Bow Valley, Alberta. *Geographical Review* **56**: 226–238.

Ntegeka V, Willems P. 2008. Trends and multidecadal oscillations in rainfall extremes, based on a more than 100-year time series of 10 min rainfall intensities at Uccle, Belgium. *Water Resources Research* **44**(7). DOI:10.1029/2007WR006471

Ogilvie RT. 1963. *Ecology of the Forests in the Rocky Mountains of Alberta.* Alberta Department of Forests. Calgary, Alberta; 62pp.

Pomeroy JW, Parviainen J, Hedstrom N, Gray DM. 1998. Coupled modelling of forest snow interception and sublimation. *Hydrological Processes* **12**: 2317–2337.

Pomeroy JW, Fang X, Ellis CR. 2012. Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrological Processes* **26**: 1891–1904. DOI:10.1002/hyp.9248

Pomeroy JW, Stewart RE, Whitfield PH. 2016a. The 2013 flood event in the Bow and Oldman River basins; causes, assessment, and damages. *Canadian Water Resources Journal* **41**: 105–117. DOI:10.1080/07011784.2015.1089190

Pomeroy JW, Fang X, Marks DG. 2016b. The cold rain-on-snow event of June 2013 in the Canadian Rockies – characteristics and diagnosis *Hydrological Processes* **30**(17): 2899–2914.

R Development Core Team. 2014. R: a language and environment for statistical computing: R Foundation for Statistical Computing.

Robichaud PR. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology* **231-232**: 220–9.

Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A. 2008. Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology* **349**: 397–410.

Rood SB, Foster SG, Hillman EJ, Luek A, Zenewich KP. 2016. Flood moderation: declining peak flows along some Rocky Mountain rivers and the underlying mechanism. *Journal of Hydrology* **536**: 174–182.

Sauder PM. 1914. Maximum flood discharge of the Bow River. *Annual Report of the Department of the Interior for the Fiscal Year Ending March 31, 1913. Sessional Paper No. 25-1914. King's Printer, Ottawa, ON*, 124-126.

Shabbar A, Khandekar M. 1996. The impact of El Niño–Southern Oscillation on the temperature field over Canada. *Atmosphere-Ocean* **43**: 401–416.

Shabbar A, Bonsal B, Khandekar M. 1997. Canadian precipitation patterns associated with the southern oscillation. *Journal of Climate* **10**: 3016–3027.

Shook KR. 2016. The 2005 flood events in the Saskatchewan River Basin: causes, assessment and damages. *Canadian Water Resources Journal* **41**: 94–104.

Shook KR, Pomeroy JW. 2012. Changes in the hydrological character of rainfall on the Canadian prairies. *Hydrological Processes* **26**: 1752–1766.

Springer J, Ludwig R, Kienzle SW. 2015. Impacts of forest fires and climate variability on the hydrology of an alpine medium sized catchment in the Canadian Rocky Mountains. *Hydrology* **2**: 23–47.

Stringer PW. 1973. An ecological study of grasslands in Banff, Jasper, and Waterton Lakes National Parks. *Canadian Journal of Botany* **51**: 383–411.

Swanson RH, Golding DL. 1982. Snowpack management on Marmot watershed to increase late season streamflow. In: *Proceedings, 50th Annual meeting, Western snow conference*, April 19–23, 1982, Reno, Nevada; pp. 215–218.

Swanson RH, Golding DL, Rothwell RL, Bernier P. 1986. *Hydrologic effects of clear-cutting at Marmot Creek and Streeter watersheds, Alberta*. Forestry Service of Canada: Edmonton, Alberta.

Trenberth KE. 1997. The definition of El Nino. *Bulletin of the American Meteorological Society* **78**(12): 2771–2777.

Troendle CA, Leaf C. 1981. Effects of timber harvest in the snow zone on volume and timing of water yield. In *Watershed Management Symposium*, Baumgartner DM (ed). Coop. Ext. Washington State Univ.: Pullman, Washington; 231–244.

Van Wagner C, Finney MA, Heathcott M. 2006. Historical fire cycles in the Canadian Rocky Mountain parks. *Forest Science* **52**: 704–717.

Veres MC, Hu Q. 2013. AMO-forced regional processes affecting summertime precipitation variations in the Central United States. *Journal of Climate* **26**: 276–90.

Waylen P, Woo M-K. 1982. Prediction of annual floods generated by mixed processes. *Water Resources Research* **18**: 1283–1286.

Waylen P, Woo M-K. 1983. Stochastic analysis of high flows generated by mixed processes. *Canadian Journal of Civil Engineering* **10**: 639–648.

White C. 1985. *Wildland Fires in Banff National Park 1880–1980, Occasional Paper No 3*: National Parks Branch, Environment Canada.

White CA. 2001. Aspen, elk, and fire in the Canadian Rocky Mountains. University of British Columbia.

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White CA, Hurd TE, Hebblewhite M, Pengelly IR. 2007. Mitigating fire suppression, highway, and habitat fragmentation effects in the Bow Valley Ecosystem, Banff National Park: preliminary evaluation of a Before-After-Control-Impact (BACI) design with path analysis. In *Monitoring the Effectiveness of Biological Conservation*. Richmond BC: FORREX. pgs 165–185.

White CA, Olmsted CE, Kay CE. 1998. Aspen, elk, and fire in the Rocky Mountain national parks of North America. *Wildlife Society Bulletin* **26**: 449–462.

White CA, Perrakis DDB, Kafka VG, Ennis T. 2011. Burning at the edge: Integrating biophysical and eco-cultural fire processes in Canada's parks and protected areas. *Fire Ecology* **7**: 74–106.

Whitfield PH. 2012. Floods in Future Climates: A Review. *Journal of Flood Risk Management* **5**: 336–365.

Whitfield PH, Burn DH, Hannaford J, Higgins H, Hodgkins GA, Marsh T, Looser U. 2012. Hydrologic Reference Networks I. The status of national reference hydrologic networks for detecting trends and future directions. *Hydrological Sciences Journal* **57**: 1562–1579.

Whitfield PH, Moore RD, Fleming SW, Zawadzki A. 2010. Pacific decadal oscillation and the hydroclimatology of western Canada - review and prospects. *Canadian Water Resources Journal* **35**: 1–28.

Whyte GH. 1914. Floods in the North Saskatchewan River drainage basin. *Annual Report of the Department of the Interior for the Fiscal Year Ending March 31*, *1913*. *Sessional Paper No. 25-1914*. *King's Printer*, *Ottawa*, *ON*, 126-128.

Whyte GH. 1916. Floods in Alberta and Saskatchewan in June and July, 1915. *Annual Report of* the Department of the Interior for the Fiscal Year Ending March 31, 1916. Sessional Paper No. 25c-1916. King's Printer. Ottawa, ON, 543–562 + colour plate A4.

Woo M-K, Waylen P. 1984. Areal prediction of annual floods generated by two distinct processes. *Hydrological Sciences Journal* **29**: 75–88.

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